

# **A Study of the Structure of the Near-Coastal Zone Water Column Using Numerical Simulations**

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## **LONG-TERM GOAL**

Our long-term goal is to understand how flows in near-coastal zone (20m to 100m) respond to a variety of forcing mechanisms including wind stresses, tidal pressure gradients, surface waves, surface heating and cooling, surface wave-bottom current interaction, and tidally generated bottom boundary currents. Because the nature of this response varies throughout the water column and depends strongly on the non-linear coupling of stratification, turbulence and flow structure characterizing the structure of the water column in this environment is a very difficult field measurement task.

## **OBJECTIVES**

It is possible to gain some insight into the physics, and into our ability to model or parameterize the physics, by looking at a more idealized version of this problem using a variety of numerical simulation approaches. We plan to develop Large Eddy Simulation Models of the flow structure in the stratified water column in the near-coastal zone which are typically subject to surface heating fluxes, wind stirring, and tidally generated bottom turbulence. Using these simulation tools we shall study the physics, and how to parameterize it, for two related flow problems in particular:

- a) Stratified tidal flows, i.e., stratified flows with oscillating pressure gradients;
- b) Wavy turbulent flows, i.e., unstratified channel flows with waves.

## **APPROACH**

Two codes have been developed for doing the proposed simulations. The first is a parallelized Navier-Stokes code for solving stratified, turbulent channel flows. This code was originally developed and implemented on the 400 node Intel Paragon XP/S supercomputer at SDSC. We are now in the process of implementing this code on the SGI parallel machine in the Environmental Fluid Mechanics Laboratory at Stanford. A description of the numerical method, speedup and performance timing measurements on Intel iPSC/860 and Paragon XP/S computers is presented in Garg et al. (1994, 1995).

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The second code is a finite-volume Navier-Stokes code developed by Zang et al. (1994). This code has been used to successfully simulate flow in a turbulent lid-driven cavity (Zang et al., 1993), and the upwelling process in a stratified, rotating flow (Zang and Street, 1995). It is currently being used, and will be used, for simulating a surface wave propagating over a turbulent flow.

## WORK COMPLETED

1. Performed simulations for the following flows related to the wavy boundary problem:
  - a) Two dimensional wavy case (2Dwavy). This simulates the flow in a domain with a wavy top and flat surfaces as the other three boundaries. The flow is driven by the second order stokes wave propagating on the top of the domain with a tangential stress applied along its surface. }
  - b) Two dimensional rectangular case (2DCL). This models a flow driven by the vortex force given by the Craik-Leibovich theory. The problem is assumed to be invariant in the streamwise direction, and the numerical domain is actually a spanwise plane observed from the downstream. The base flow for this case is a linear current and a Stokes drift.
  - c) Three dimensional wavy flow (3Dwavy). This problem is similar to the two dimensional wavy flow except that the spanwise variations are also considered.
  - d) Three dimensional channel flow with Craik-Leibovich forcing (3DCL). This is an extension to the two dimensional rectangular case, with considerations of the streamwise variations.
2. Analysed the results from these simulations. The first two cases are mainly used as benchmarks. The 2Dwavy case (a) was tested against Longuet-Higgins' (1953) theory, and the 2DCL (b) case is compared with the instability study performed by Garg et al. (1993) using the Craik-Leibovich theory. The 3Dwavy (c) case is useful for studying wave-current interactions. The steady state results from the 2Dwavy (a) case are also used as the initial base flow for the 3Dwavy flows. Random white noises of small magnitude are imposed on the base flow. The simulation results are being analyzed to elucidate the underlying physics of the emerging 3D flow. The Craik-Leibovich theory is being verified by comparing the 3Dwavy simulations with the results from the 2DCL runs, which are for constant eddy viscosity cases, and the solutions from the 3DCL runs, which are for cases with turbulent models.
3. Performed Direct Numerical Simulations (DNS) of stratified sheared homogeneous turbulence over a wide range of initial dimensionless shear rates and turbulent Reynolds numbers. These simulations were performed to test the published result of Jacobitz et al (1997) that the stationary Richardson number is a function not only of the Reynolds number but also of the dimensionless shear rate. The simulations were also performed to test some new ideas for the scaling of stratified turbulence.

## RESULTS

Results from the simulations of the wavy surface flows are as follows:

## 1. Model validation using cases 2Dwavy and 2DCL

a) If the surface wave of 2Dwavy cases is free from tangential stress, the flow then depends on three parameters: the Reynolds number based on the velocity of the Stokes drift, the wavelength of the surface wave, and the waveslope of the surface wave. Previously we only studied the effects of the Reynolds number on the Eulerian mean flow. Further studies are performed on the effects of the other two controlling parameters. By normalizing the slope of the Eulerian mean flow obtained numerically with the leading second order term derived in Longuet-Higgins' 1953 paper, we found that the resulting value varies not only with the Reynolds number, but also with the wavelength and the waveslope. Furthermore our results indicate that besides the Longuet-Higgins' second order term, higher order terms are also resolved from the numerical solution.

b) Scaling analysis suggests that the Stokes drift is the appropriate velocity to use in scaling flows of this type. The numerical code with the new scaling is validated with a two dimensional reference flow in a rectangular domain with Craik-Leibovich forcing, using a more realistic Stokes drift than for previous calculations. We found:

1. When the development of the kinetic energy computed from the spanwise perturbation velocity over time is compared with the growth rate given by theory, that the perturbation to the base flow is amplified with initial growth rates that are in agreement with the linear instability analysis.
2. Two counter-rotating langmuir cells are formed and grow to the final steady state in which a convergence zone and a divergence zone can be identified. The Langmuir cells are asymmetric, as observed in the field. Moreover, the gradients of the vorticity are greater near the top surface as the vortex force is bigger there due to the exponential distribution of the Stokes drift.
3. It shows that the maximum downwelling velocity is located just above half of the depth of the cell, which agrees with experimental observations (Nepf and Monismith, 1991). Furthermore, the maximum downwelling velocity is greater than the maximum upwelling velocity, as observed in the field study by Weller and Price (1988)

## Evaluation of Theory using 3Dwavy and 3DCL

c) The streamwise vorticity on a spanwise plane at the trough of the surface wave is examined at different times. Initially, at time there are four counter-rotating cells near the top surface. Their vorticity increases with time as they deepen downward. At a later time the four cells have merged into two bigger cells, which continue to evolve until they reach the final steady state. This cell merging process is similar to that obtained by Li and Garrett(1993, 1997) with their simulations using Craik-Leibovich theory.

d) Unlike the 2DCL results, the Langmuir cells occur on top of a wave field. The wave field causes the cell to have the minimum size at the backward slope of the wave and the maximum size at the forward slope of the wave. Therefore, a fluid particle would experience larger acceleration toward the convergence zone at the forward slope than at the backward slope.

- e) The basic assumption of the Craik-Leibovich theory , the disparate time scale, is verified by comparing our 3Dwavy results with that obtained from the 2DCL simulation, in which the Craik-Leibovich equations are solved. The base flow of the 2DCL case contains a Stokes drift corresponding to the wavenumber of the surface wave, and a linear mean current with the same slope as that of the initial mean flow under the top boundary layer in the 3Dwavy case. Thus the current for the 2DCL incorporates the effects of both wind stress and the Eulerian mean flow.
- f) The comparison of the 3Dwavy case and the 2DCL case indicates that without the averaging over a wave field, the flow obtained by integrating the Navier-Stokes equations directly has great similarity to that given by the Craik-Leibovich theory. Both predict the correct characteristics of Langmuir circulations observed in the field. Therefore, the averaging used in Craik-Leibovich theory seems to be based on a sound assumption.

Results for the DNS simulations are as follows (see Shih et al, 1998) :

4. At low Reynolds number the stationary Richardson number depends on both the Reynolds number and the dimensionless shear number. At higher Reynolds number, however, we established that the dimensionless shear number evolves to a constant regardless of its initial value and that the stationary Richardson number varies only with Reynolds number.
5. The turbulent Froude number, which is based on local turbulence quantities, provides a far more enlightening description of stratification effects than does the gradient Richardson number which is based on global quantities

## **IMPACT/APPLICATIONS**

The simulations completed demonstrate the intrinsic value of DNS and LES in that it allows us to calculate each term in a model or parameterization of the extant physics. Evaluation of existing turbulence closure models or commonly used sub-grid-scale parameterizations is therefore a lot more complete than with experiments alone. Our simulations of the channel flows are the first important step in developing a code for studying the evolution of the density structure of the water column in the near-coastal ocean. Once completed this code will be a valuable research tool for use in conjunction with field work currently underway involved in measuring flowfields in the near-coastal ocean.

## **TRANSITIONS**

The numerical data-bases developed have been analysed by the PI's in other research projects and the data has been used by researchers at other institutions.

## **RELATED PROJECTS**

A Study of the structure of stratified flows - NSF - (Monismith PI)  
 The structure of turbulence and other motions beneath an air-water interface - ONR -(Monismith Co-PI)

An Experimental Study of a Breaking Interfacial Wave - NSF- (Koseff PI)

Chemical Sensing in the Marine Environment -ONR - (Monismith PI)

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